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Research Article

Admission Control and Interference Management in Dynamic Spectrum Access Networks

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We study two important aspects to make dynamic spectrum access work in practice: the admission policy of secondary users (SUs) to achieve a certain degree of quality of service and the management of the interference caused by SUs to primary users (PUs). In order to limit the forced termination probability of SUs, we evaluate the Fractional Guard Channel reservation scheme to give priority to spectrum handovers over new arrivals. We show that, contrary to what has been proposed, the throughput of SUs cannot be maximized by configuring the reservation parameter. We also study the interference caused by SUs to PUs. We propose and evaluate different mechanisms to reduce the interference, which are based on simple spectrum access algorithms for both PUs and SUs and channel repacking algorithms for SUs. Numerical results show that the reduction can be of one order of magnitude or more with respect to the random access case. Finally, we propose an adaptive admission control scheme that is able to limit simultaneously the forced termination probability of SUs and what we define as the probability of interference. Our scheme does not require any configuration parameters beyond the probability objectives. Besides, it is simple to implement and it can operate with any arrival process and distribution of the session duration.

1. Introduction

Cognitive radio networks are envisaged as the key technology to realize dynamic spectrum access (DSA). Such paradigm shift in wireless communications aims at solving the scarcity of radio spectrum [1–4]. The DSA concept proposes to boost spectrum utilization by allowing DSA users (SUs) to access the licensed wireless channel in an opportunistic manner so that interference to licensed users (PUs) is kept to a minimum. The idea of DSA is undoubtedly compelling and its realization will induce a huge advance in wireless communications. However, there are many challenges and open questions that have to be addressed before DSA networks become practically realizable [5, 6].

To fulfill the requirement of minimum interference to PUs, a SU with an ongoing communication must vacate the channel when a licensed user is detected. The SU may switch to a different unused spectrum band which is referred to as spectrum mobility or *spectrum handover* (SH). If no available bands can be found or the SH procedure is not

implemented, one or more SUs will be forced to terminate their sessions. From the user's perspective, it is generally assumed that the interruption of an ongoing session is more annoying than denying initial access [7]. Therefore, blocking the request of a new SU session, even if there are enough free resources, can be employed as a strategy to reduce the number of SU sessions forcedly terminated and the interference caused to PUs.

A variety of studies that focus on priority mechanisms to handle conventional handovers in cellular networks have appeared in the literature, see [8] and references therein. However, SH and conventional handover are different in nature and also from a modeling perspective.

In this paper, we focus on the study of the Quality of Service (QoS) perceived by PUs and SUs at the session level. We employ the same rather simple model than [9], which is enhanced to include an extension of the reservation scheme so that a noninteger number of channels can be reserved for SH. Such extension borrows the idea from the Fractional Guard Channel scheme that was introduced

in cellular networks [10]. Furthermore, our numerical results for the system throughput are qualitatively different from those obtained in [9] leading to completely different conclusions, especially in what concerns the optimum system configuration.

Interference management has been identified as one of the critical challenges to make DSA networks work in practice [6]. Common DSA proposals take a reactive approach, in which SUs perform SH only after detecting PU interference. To detect PU activity in the same band, a SU must perform *spectrum sensing*, which requires to pause any ongoing transmission and causes a considerable performance penalty [6]. Additionally, SUs must execute spectrum sensing frequently to react quickly when a PU occupies the same band [11]. To handle both requirements, transmission and spectrum sensing episodes are typically interleaved in a cyclic manner [12, 13].

We study the interference management problem from the traffic perspective. Our perception is that the mechanisms we propose might have a complementary role with respect to those defined at the physical layer. Our work is motivated by the fact that although simple spectrum access and channel repacking algorithms have been proposed in the classical communications literature their application to DSA systems has not been explored yet. In this paper, we assume that the primary network follows a predefined deterministic pattern when searching for free channels to set up a new session. The secondary network is aware of the rule followed by the primary network and uses this information in its own benefit but also in that of the primary network. The secondary network senses and assigns free channels to SUs in the reversed order that they will be occupied by PUs, hence reducing the probability of SUs having to vacate the assigned channel and causing interference to PUs. The probability of causing interference may be further reduced by performing a channel rearrangement to SUs after the release of channel. The mechanisms described above entail a minimal cooperation of the primary network, which in turn redound in a reduced interference for PUs. The idea of the primary network cooperating with the secondary one has also been proposed in [14].

We will show that both the *forced termination probability* and the *interference* created by the operation of SUs upon PUs can be controlled by limiting the access of SUs. This finding motivated us to design an admission control scheme for SUs that is able to limit simultaneously both the forced termination probability of SUs and what we define as the probability of interference. We show that both the forced termination probability and the interference caused to PUs are highly dependent on system parameters and on the arrival processes and service distributions. However, the proposed scheme is self-adaptive and does not require any configuration parameters beyond the targeted QoS objectives. Besides, it does not rely on any particular assumptions on the traffic characteristics; that is, it can operate with any arrival process and distribution of the session duration.

The rest of the paper is structured as follows. The different models of the systems studied are described in Section 2. In Section 3, we evaluate numerically the impact

of incorporating admission control on the forced termination of SUs and also the impact of deploying channel allocation with preference and repacking on the interference. In Section 4, we propose and evaluate a novel adaptive admission control scheme that is able to limit simultaneously both the forced termination probability and the interference. Finally, Section 5 concludes the paper.

2. Model Description

We consider an infrastructure-based DSA network where PUs and SUs cooperate. Infrastructure-based DSA networks have been proposed in [2, 6, 15]. We assume that channels available for system operation are numbered according to the order in which they are assigned by the primary network; that is, we consider that to setup a PU session, the system searches from left (low-channel numbers) to right (high-channel numbers) until enough free channels can be allocated to the new session. Conversely, to setup a new SU communication the system searches from right (high-channel numbers) to left (low-channel numbers). We call this mechanism *channel allocation with preference* (CAP). Additionally, once a PU or a SU session has finished, a *channel repacking* of ongoing SU sessions can be performed to avoid interfering with future PU arrivals. Channel repacking can be triggered when, after a session completion, there exist ongoing SU sessions that can be moved to higher channel numbers; that is, there exist ongoing SU sessions that can perform a preventive SH to avoid creating future interference.

The system has a total of C resource units, being the physical meaning of a unit of resource dependent on the specific technological implementation of the radio interface. For the sake of mathematical tractability, we make the common assumptions of Poisson arrival processes and exponentially distributed service times. However, we also study the impact that distributions different than the exponential for the session lifetime have on system performance. The arrival rate for PU (SU) sessions to the system is λ_1 (λ_2), and a request consumes b_1 (b_2) resource units when accepted, $b_i \in \mathbb{N}$, $i = 1, 2$. For a packet-based air interface, b_i represents the effective bandwidth of the session [16, 17]. We assume that $b_1 = N$, $b_2 = 1$ and $C = M \times N$, therefore the system resources can be viewed as composed by $M = C/N$ bands for PUs or $M \times N$ subbands or channels for SUs. In other words, the maximum number of ongoing PU sessions is M and of SU sessions is $M \times N$. The service rates for primary and secondary sessions are denoted by μ_1 and μ_2 , respectively.

We study seven different systems that can be aggregated into three groups. The characteristics of each of the seven systems are defined in Table 1. The second (SH), third (AC-FT) and sixth (AC-FT&I) columns refer, respectively, to spectrum handoff mechanism, the admission control (AC) scheme to limit the forced termination (FT) of SUs, and the adaptive AC scheme that limits simultaneously the forced termination probability perceived by SUs (P_2^{ft}) and the interference caused to PUs. On these columns, a “Y” means that the systems implements the corresponding mechanism and a “N” that it is not implemented. The fourth (CA) and fifth (RP) columns refer, respectively, to the

TABLE 1: Features of the systems studied.

System	SH	AC-FT	CA	RP	AC-FT&I
S1	N	N	R	N	N
S2	Y	Y	R	N	N
S3a	N	N	P	N	N
S3b	Y	N	P	N	N
S4	Y	N	P	Y	N
S5a	N	Y	P	N	Y
S5b	Y	Y	P	Y	Y

channel allocation, which can be either random (“R”) or with preference (“P”); and the repacking mechanism, which is either implemented (“Y”) or not (“N”).

In the following subsections, we introduce analytical and simulation models to study the systems described in Table 1. In Section 2.1 we present two continuous-time Markov chain (CTMC) models that define the operation of systems 1 (S1) and 2 (S2). The aim is to use these models to evaluate the effectiveness of AC to limit P_2^{ft} . Numerical results of this evaluation are shown in Section 3. In Section 2.2, we briefly outline two CTMC models that define the operation of systems 3 (S3) and 4 (S4). The aim is to use these models to compare the interference in a system deploying the proposed CAP and repacking schemes with the interference in the conventional random channel allocation scheme. Numerical results of this evaluation are also shown in Section 3. Finally, the model of the adaptive AC scheme deployed in system 5 (S5) and its evaluation is described in Section 4.

2.1. AC Scheme to Limit the Forced Termination of SUs. We denote by $\mathbf{x} = (x_1, x_2)$ the system state vector, when there are x_1 ongoing PU sessions and x_2 SU sessions. Let $b(\mathbf{x})$ represent the amount of occupied resources at state \mathbf{x} , $b(\mathbf{x}) = x_1N + x_2$. The system evolution along time can be modeled as a multidimensional Markov process whose set of feasible states is

$$\mathcal{S} := \{\mathbf{x} = (x_1, x_2) : x_1N + x_2 \leq C\}. \quad (1)$$

We develop two analytical models to evaluate the performance of DSA systems measured by the forced termination probability of SUs.

2.1.1. System 1. This first system is characterized by not supporting SH, deploying the *Complete Sharing* admission policy, that is, all SU requests are accepted while free resources are available, deploying a random channel allocation scheme with no repacking.

A PU arrival in state \mathbf{x} will force the termination of k SUs, $k = 0, \dots, \min(x_2, N)$, with probability

$$p(\mathbf{x}, k) = \frac{\binom{N}{k} \binom{(M-x_1-1)N}{x_2-k}}{\binom{(M-x_1)N}{x_2}}. \quad (2)$$

when k SUs are in the channels occupied by the newly arrived PU session, while the other $(x_2 - k)$ are distributed in the other $(M - x_1 - 1)N$ channels. Clearly,

$$\sum_{k=0}^{\min(x_2, N)} p(\mathbf{x}, k) = 1. \quad (3)$$

Let $r_{\mathbf{xy}}$ be the transition rate from \mathbf{x} to \mathbf{y} , $\mathbf{x}, \mathbf{y} \in \mathcal{S}$, and be \mathbf{e}_i a vector whose entries are all 0 except the i th one, which is 1, then

$$r_{\mathbf{xy}} = \begin{cases} p(\mathbf{x}, k)\lambda_1 & \text{if } \mathbf{y} = \mathbf{x} + \mathbf{e}_1 - k\mathbf{e}_2, \\ & k = 0, \dots, \min(x_2, N), \\ \lambda_2 & \text{if } \mathbf{y} = \mathbf{x} + \mathbf{e}_2, \\ x_i\mu_i & \text{if } \mathbf{y} = \mathbf{x} - \mathbf{e}_i, i = 1, 2, \\ 0 & \text{otherwise.} \end{cases} \quad (4)$$

Figure 1 shows the state diagram and transition rates of the CTMC that models the system dynamics. The global balance equations are expressed as

$$\pi(\mathbf{x}) \sum_{\mathbf{y} \in \mathcal{S}} r_{\mathbf{xy}} = \sum_{\mathbf{y} \in \mathcal{S}} \pi(\mathbf{y}) r_{\mathbf{yx}} \quad \forall \mathbf{x} \in \mathcal{S}, \quad (5)$$

where $\pi(\mathbf{x})$ is the stationary probability of state \mathbf{x} . The stationary distribution $\{\pi(\mathbf{x})\}$ is obtained from (5) and the normalization equation.

The blocking probability for SU requests, P_2 , and the SUs forced termination probability, P_2^{ft} , can be determined from the stationary distribution. Let us define

$$k(\mathbf{x}) = \sum_{r=0}^{\min(x_2, N)} r p(\mathbf{x}, r). \quad (6)$$

Clearly, $k(\mathbf{x})$ is the mean number of SUs that are forced to terminate upon the arrival of a PU in state \mathbf{x} . Then,

$$P_2 = \sum_{\mathbf{x} \in \mathcal{S}, \mathbf{x} + \mathbf{e}_2 \notin \mathcal{S}} \pi(\mathbf{x}), \quad (7)$$

$$P_2^{\text{ft}} = \frac{\sum_{\mathbf{x} \in \mathcal{S}} k(\mathbf{x}) \pi(\mathbf{x}) \lambda_1}{\lambda_2 (1 - P_2)}. \quad (8)$$

Note that P_2^{ft} is the ratio of the forced termination rate to the acceptance rate.

Finally, the SUs throughput, that is, the successful completion rate of SUs is determined by

$$\text{Th}_2 = \lambda_2 (1 - P_2) (1 - P_2^{\text{ft}}). \quad (9)$$

2.1.2. System 2. This system is characterized by supporting SH, deploying the *Fractional Guard Channel* admission policy and deploying the random channel allocation scheme with no repacking.

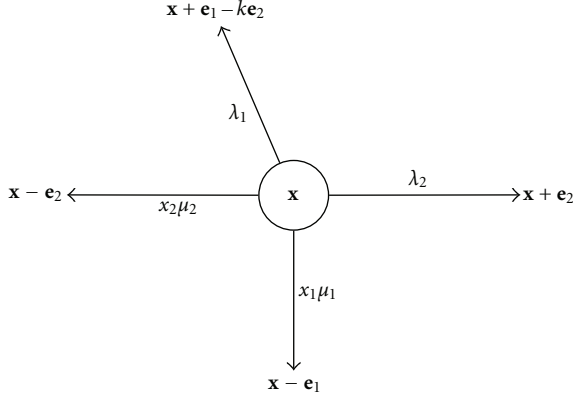


FIGURE 1: State transition rates of the CTMC from a generic state $\mathbf{x} \in \mathcal{S}$.

When a SU new setup request arrives and finds the system in state \mathbf{x} , an admission decision is taken according to the number of free resource units available:

$$C - b(\mathbf{x} + \mathbf{e}_2) \begin{cases} > \lfloor t \rfloor & \text{accept,} \\ = \lfloor t \rfloor & \text{reject with probability } t - \lfloor t \rfloor, \\ < \lfloor t \rfloor & \text{reject,} \end{cases} \quad (10)$$

where we denote by $t \in [0, C]$, the admission control threshold; that is, the average number of resource units that must remain free after accepting the new SU requests must be t or higher. Clearly, these resources are reserved for SUs performing SH. Then, increasing t causes a reduction of the forced termination probability but, at the same time, increases the blocking probability perceived by new SU requests and vice versa. Note also that PUs are unaffected by the admission policy, as SUs are transparent to them.

A PU arrival in state \mathbf{x} will not force the termination of SUs when the system state complies with $C - b(\mathbf{x}) \geq N$, as the execution of SH will allow SUs to continue their ongoing session in a new unused channel, which are guaranteed to exist given the condition above. On the other hand, when $C - b(\mathbf{x}) < N$, $x_1 < M$, a PU arrival will preempt $b(\mathbf{x} + \mathbf{e}_1) - C$ SUs. Let $k(\mathbf{x})$ be the number of preemptions in state \mathbf{x} , then

$$k(\mathbf{x}) = \min\{r \in \mathbb{N} \mid b(\mathbf{x} + \mathbf{e}_1 - r\mathbf{e}_2) \leq C\}. \quad (11)$$

Note that $k(\mathbf{x}) = 0$ when $C - b(\mathbf{x}) > N$, that is, it will be null for a high portion of the state space.

As before, let r_{xy} be the transition rate from \mathbf{x} to \mathbf{y} , $\mathbf{x} \in \mathcal{S}$, then

$$r_{xy} = \begin{cases} a_1(\mathbf{x})\lambda_1 & \text{if } \mathbf{y} = \mathbf{x} + \mathbf{e}_1 - k(\mathbf{x})\mathbf{e}_2, \\ & k = 0, \dots, \min(x_2, N), \\ a_2(\mathbf{x})\lambda_2 & \text{if } \mathbf{y} = \mathbf{x} + \mathbf{e}_2, \\ x_i\mu_i & \text{if } \mathbf{y} = \mathbf{x} - \mathbf{e}_i, \\ 0 & \text{otherwise.} \end{cases} \quad (12)$$

The coefficients $a_1(\mathbf{x})$ and $a_2(\mathbf{x})$ denote the probabilities of accepting a PU arrival and a SU arrival in state \mathbf{x} , respectively. It is clear that $a_1(\mathbf{x}) = 1$, if $\mathbf{x} + \mathbf{e}_1 - k(\mathbf{x})\mathbf{e}_2 \in \mathcal{S}$, and 0 otherwise. Given a policy setting t , $a_2(\mathbf{x})$ is determined as follows:

$$a_2(\mathbf{x}) = \begin{cases} 1 & \text{if } C - b(\mathbf{x} + \mathbf{e}_2) > \lfloor t \rfloor, \\ 1 - (t - \lfloor t \rfloor) & \text{if } C - b(\mathbf{x} + \mathbf{e}_2) = \lfloor t \rfloor, \\ 0 & \text{otherwise.} \end{cases} \quad (13)$$

Figure 1 shows the state transition rates of the CTMC that models the system dynamics. The stationary distribution, $\{\pi(\mathbf{x})\}$, is obtained by solving the global balance equations (5) together with the normalization equation. The blocking probability for SU requests, P_2 , the SUs forced termination probability, P_2^{ft} , and the SUs throughput, Th_2 , are then computed using (7), (8) and (9), respectively.

The analytical models described above have been validated through computer simulations. The simulation models we designed mimic the behavior of the physical system, in other words, the original system itself is simulated instead of simulating just the CTMC. Thus, the validation offers a guarantee on the correctness of the whole modeling process, and not only about the generation and solution of the global balance equations of the CTMC.

2.2. CAP Scheme to Limit the Interference Caused to PUs.

We assume that the SUs vacating rate induced by the arrival of new PU sessions is a measure of the interference caused by SUs to PUs, and we pursue to determine its value when deploying the spectrum access and channel repacking algorithms described in Section 1. Besides, we compare it to the one obtained when deploying the conventional random allocation scheme. A similar metric was used in [13] to measure the interference.

When the system supports SH the channel allocation and repacking algorithms have no impact on the performance perceived by the SUs; that is, their blocking and forced termination probabilities are not affected. Clearly, the finding of free channels by arriving or vacated SUs depends only on the number of ongoing PU and SU sessions and not on their physical disposition on the spectrum.

It should be noted that repacking for PUs is not considered. If the system deploys SH, CAP and repacking for SUs, doing repacking for PUs would only affect the algorithm followed to find a free channel upon the arrival of a SU, but not to the system performance (P_2^{ft} and interference). As described above, P_2^{ft} is not affected by the channel allocation and repacking algorithms used. In the same system, a PU arrival will experience interference when there are SUs occupying the PU band with the lowest order available. Clearly, this occurs when there are not enough free channels to accommodate the newly arrived PU without some SUs vacating the channel they are using ($C - b(\mathbf{x}) < N$) then a previous repacking of PUs would have not helped.

TABLE 2: Transition rates in system 3b with $M = 2$.

Current state	Next state	Transition rate
(i, j)	(P, k)	λ_1
	$k = \min(j + i, N)$	
(i, P)	(P, P)	
(P, j)	(P, P)	λ_2
$(i, j), j < N$	$(i, j + 1)$	
$(i, N), i < N$	$(i + 1, N)$	
$(P, j), j < N$	$(P, j + 1)$	
$(i, P), i < N$	$(i + 1, P)$	
(i, P)	$(i, 0)$	μ_1
(P, j)	$(0, j)$	
(P, P)	$(0, P), (P, 0)$	
(i, j)	$(i - 1, j), (i, j - 1)$	$(i + j)\mu_2$
(i, P)	$(i - 1, P)$	$i\mu_2$
(P, j)	$(P, j - 1)$	$j\mu_2$

2.2.1. System 3. System 3b (3a) is characterized by supporting (not supporting) SH, deploying the *Complete Sharing* admission policy, deploying CAP and no repacking.

For the type of system under study, the state space of its CTMC model grows very quickly with the number of channels, as the state representation must describe not only the number of ongoing PU and SU sessions, but also the disposition of the allocated channels on the spectrum. More specifically, the number of states is $(N + 2)^M$. This makes the solution of the CTMC intractable for any practical scenario.

Instead, we developed a simulation model and validated it with the analytical model of a simple scenario. This scenario has $M = 2$ bands for PUs and $M \times N$ subbands or channels for SUs. The set of feasible states is

$$\mathcal{S} := \{\mathbf{y} = (y_1, y_2) : y_1, y_2 \in \{P, 0, \dots, N\}\}, \quad (14)$$

where y_1 (y_2) describes the state of the N leftmost (rightmost) channels. When $y_i = 0$ the band is empty, when $y_i = P$ it is occupied by a PU, otherwise the number of SUs in the band can be $y_i = 1, \dots, N$. The transition rates of the CTMC that models system 3b are displayed in Table 2.

Note that, for example, at state $(1, P)$, where there is one SU occupying one channel (out of N) in the first band of N channels and one PU occupying the second band, the actual channel allocated to the SU cannot be determined, but this information is irrelevant for the performance parameters of interest. When $N = 2$, the system has 16 states, independently of SH being supported or not.

As an example, for a system supporting SH and CAP, the vacating rate γ^v and the forced termination rate γ^{ft} can be determined from (15) and (16). The first term in (15) accounts for the contribution to the SUs vacation rate of states with no PUs in the system. In these states, a PU arrival will occupy the first band, vacating i SUs. The second and third terms account for the contribution of the states where there is a PU in the first or the second band, respectively. Then, the arrival of a new PU would vacate j or i SUs, respectively. The first term in (16) accounts for the

contribution to the SUs forced termination rate of states with no PUs in the system. Note that if i SUs are found in the first band, the arrival of a PU will force the termination of one SU when there are $N - i + 1$ SUs in the second band, of two SUs when there are $N - i + 2$ SUs in the second band, and so on. The second and third terms clearly account for the contribution of states where there is a PU in the first and second band, respectively,

$$\gamma^v = \lambda_1 \left[\sum_{i=0}^N \sum_{j=0}^N i\pi(i, j) + \sum_{j=0}^N j\pi(P, j) + \sum_{i=0}^N i\pi(i, P) \right], \quad (15)$$

$$\gamma^{\text{ft}} = \lambda_1 \left[\sum_{i=0}^N \sum_{j=0}^i j\pi(i, N - i + j) + \sum_{j=0}^N j\pi(P, j) + \sum_{i=0}^N i\pi(i, P) \right]. \quad (16)$$

To compare the results of the analytical and simulation models we selected three parameters: the blocking probabilities of PUs and SUs, and the forced termination probability of SUs. For both systems, with and without SH support, results clearly indicate a close agreement between the analytical and simulation models.

2.2.2. System 4. This system is characterized by supporting SH, deploying the *Complete Sharing* admission policy, deploying CAP and repacking (CAP+RP).

Clearly, repacking can be triggered when either a PU or a SU leaves the system. Using the notation defined in the previous section for a system with $M = N = 2$, repacking would take place, for example, when a SU leaves from the upper band and the system state changes from $(1, 2)$ to $(1, 1)$. Note that as $N = 2$, a maximum of two SUs fit into the upper band. At this point, it is more convenient to move the SU in the lower band to the empty channel in the upper band, avoiding in this way future interference if a PU arrives. Then, repacking would make the system move from state $(1, 1)$ to state $(0, 2)$ instantaneously.

As in the previous section, we evaluate the system by simulation and validate the simulation model by a simple analytical model. For $M = N = 2$, the analytical model has 12 states, clearly less states than in a system without repacking, as now some states are not feasible, as shown in the previous example.

To compare the results of the analytical and simulation models we selected the same parameters of merit. Again, these results indicate an excellent agreement between the analytical and simulation models.

3. Effectiveness of the Proposed Mechanisms

In this section we evaluate the effectiveness of incorporating the Fractional Guard Channel admission policy to limit the P_2^{ft} , as well as the effectiveness of incorporating CAP and repacking to limit the interference caused to PUs.

Unless otherwise specified, the reference scenario for the numerical evaluation is defined by: $M = 10$, $N = 8$, $C = M \times N = 80$, $\mu_1 = 1$ and $\mu_2 = 1$. In some scenarios, we consider that the load offered by PUs is such that their

blocking probability is $P_1 = 0.01$, which is achieved at $\lambda_1 = 4.4612$. Following common conventions, we do not specify the unit of the rates although typical values are expressed in s^{-1} . For the simulation result 95% confidence intervals are represented. The confidence intervals have been computed using 15 different simulation runs initialized with different seeds.

3.1. Effectiveness of AC to Limit the P_2^{ft} . The throughput achieved by SUs in systems 1 and 2 is shown in Figure 2, where we depict both the results of the analytical and the simulation models. Note the excellent agreement between the analytical and simulation results. Note also that the diameter of the confidence intervals are really small. This is the reason why confidence intervals will not be shown in the rest of the figures.

The authors of [9] suggest that a natural way of configuring a DSA system of similar characteristics to ours is to choose t for each SU arrival rate, such that the Th_2 is maximized. As observed in previous figures, it is not possible to determine an optimum operating point beyond the obvious one that is to deploy SH and $t = 0$. We believe that the role of reservation in DSA systems might be the same as its classical role in cellular systems; that is, to limit the forced termination probability of SUs. Note also that for the reservation values deployed, Th_2 is always higher when deploying SH and reservation than when not deploying SH. Deploying SH reduces the forced termination rate, which increases the successful completion rate.

One of the most interesting results of the study is the evolution of P_2^{ft} with the SUs arrival rate, which is shown in Figure 3. Observe that it seems to have a counterintuitive behavior. Intuitively, one would expect that P_2^{ft} should increase with the SUs arrival rate. However in a system without SH it has the opposite behavior. Note also that in a system with reservation, and particularly for some reservation values like $t = 10$ or higher, the forced termination first decreases, attaining a minimum, and then increases. The P_2^{ft} depends on the ratio of forced terminations to accepted sessions. By comparing the evolution of the forced termination rate with the SUs acceptance rate for the interval of arrival rates of interest (not shown here), these phenomena can be easily explained.

As expected, the P_2^{ft} can be controlled by adapting the threshold t according to the system traffic load.

3.2. Effectiveness of CAP and Repacking to Limit γ^v . To evaluate the effectiveness of CAP and repacking we obtained the evolution of the SUs vacating rate γ^v with λ_1 in systems 2, 3a, and 4, when $\lambda_2 = 20$. We chose $\lambda_2 = 20$ as the P_2^{ft} is around 0.1 for a system with SH and $\lambda_1 = 4.4612$, which we consider a practical value. Recall that system 2 (S2) deploys the conventional random channel allocation algorithm, while systems 3a (S3a) and 4 (S4) deploy CAP and CAP and repacking (CAP+RP), respectively. To highlight the results of the study, we represent in Figure 4 what we define as the *interference reduction factor*; that is, the ratios $\gamma^v(S2)/\gamma^v(S3a)$ and $\gamma^v(S2)/\gamma^v(S4)$.

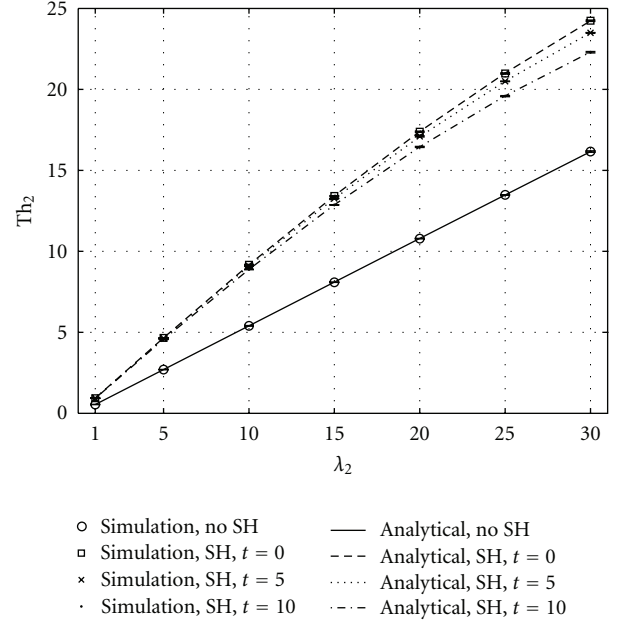


FIGURE 2: Throughput of SUs with the arrival rate of SUs when $\lambda_1 = 4.4612$.

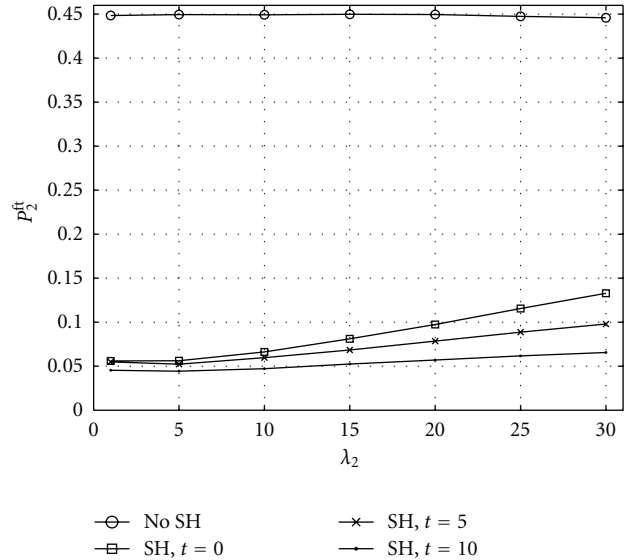


FIGURE 3: Forced termination of SUs with the arrival rate of SUs, when $\lambda_1 = 4.4612$.

Clearly, the proposed mechanisms are quite effective as they reduce the vacating rate induced by the arrival of PUs by approximately one order of magnitude or more for practical operating values. Note also that, as expected, the interference reduction factor is higher when repacking is used.

4. Adaptive Admission Control Scheme

In this section, we describe an adaptive admission control scheme that is able to limit simultaneously both the forced

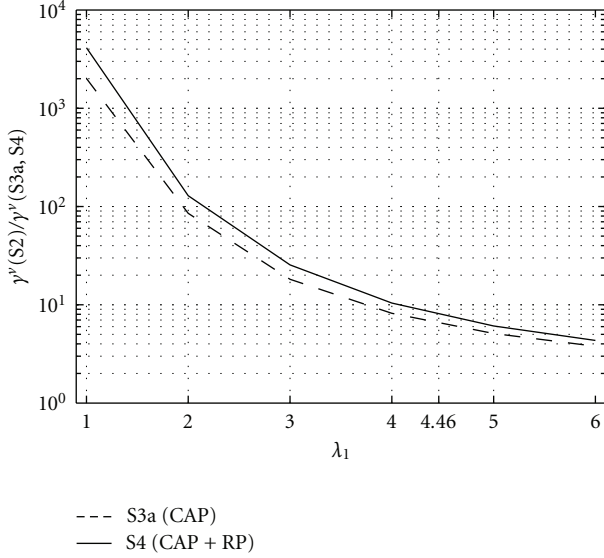


FIGURE 4: Interference reduction factor with the arrival rate of primary users when $\lambda_2 = 20$.

termination probability of SUs and the interference caused to PU communications by the operation of the SUs.

Our scheme generalizes a novel adaptive AC strategy introduced in [18] and developed further in [19], which operates in coordination with the well-known trunk reservation policy named Multiple Guard Channel (MGC). However, one of the novelties of the new proposal is that now the adaptive scheme is able to control simultaneously multiple objectives for the same arrival flow (SU arrivals), as opposed to only one objective per flow in previous proposals.

The definition of the MGC policy is as follows. One threshold parameter is associated with each objective. For example, in a system with two objectives, one for the P_2^{ft} and another for the interference. Let $t^{\text{ft}}, t^{\text{if}} \in \mathbb{N}$ be their associated thresholds. Then, a SU arrival in state \mathbf{x} is accepted if $b(\mathbf{x} + \mathbf{e}_2) \leq t$, $t = \min\{t^{\text{ft}}, t^{\text{if}}\}$, and blocked otherwise. Therefore, t is the amount of resources that SUs have access to and decreasing (increasing) it reduces (augments) the acceptance rate of SU requests, which will in turn decrease (increase) both P_2^{ft} and the interference. Note that the definition of t in this section and in Section 2 are different.

For the sake of clarity, the operation of our scheme is described assuming that arrival processes are stationary and the system is in steady state. We denote by B_2^{ft} the objective for the forced termination probability perceived by SUs (P_2^{ft}). In practice, we can assume without loss of generality that B_2^{ft} can be expressed as a fraction $n^{\text{ft}}/d^{\text{ft}}$, $n^{\text{ft}}, d^{\text{ft}} \in \mathbb{N}$. When $P_2^{\text{ft}} = B_2^{\text{ft}}$, it is expected that, in average, n^{ft} forced termination events and $(d^{\text{ft}} - n^{\text{ft}})$ successfully completed SU session events, will occur out of d^{ft} accepted SU session events. For example, if the objective is $B_2^{\text{ft}} = 1/100$, then $n^{\text{ft}} = 1$ and $d^{\text{ft}} = 100$. It seems intuitive to think that the adaptive scheme should not change t^{ft} when the system is meeting its forced termination probability objective and, on the contrary, adjust it on the required direction when the perceived P_2^{ft} is different from its objective.

Given that the MGC policy uses integer values for the threshold parameters, to limit P_2^{ft} to its objective $B_2^{\text{ft}} = n^{\text{ft}}/d^{\text{ft}}$, we propose to perform a probabilistic adjustment in the following way.

- (i) At the arrival of a PU, if it forces the termination of m SUs, do $\{t^{\text{ft}} \leftarrow t^{\text{ft}} - m\}$ with probability $1/n^{\text{ft}}$.
- (ii) When a SU session is accepted, do $\{t^{\text{ft}} \leftarrow t^{\text{ft}} + 1\}$ with probability $1/d^{\text{ft}}$.

Intuitively, under stationary traffic conditions, if $P_2^{\text{ft}} = B_2^{\text{ft}}$ then, on average, t^{ft} will be increased by 1 and decreased by 1 every d^{ft} accepted requests, that is, its mean value is kept constant.

We define a new measure for the interference by considering the fraction of PU arrivals that vacate exactly n SUs, $n > 0$, and denote it by $P^{\text{if}}(n)$. Let us denote its objective by $B^{\text{if}}(n) = n_n^{\text{if}}/d_n^{\text{if}}$ and the admission control threshold associated to it by t_n^{if} . Then, to limit $P^{\text{if}}(n)$ to its objective, we propose to perform the following probabilistic adjustment at the arrival of each PU.

- (i) With probability $1/d_n^{\text{if}}$ do $\{t_n^{\text{if}} \leftarrow t_n^{\text{if}} + 1\}$.
- (ii) Additionally, if it vacates exactly n SUs, then with probability $1/n_n^{\text{if}}$ do $\{t_n^{\text{if}} \leftarrow t_n^{\text{if}} - 1\}$.

Again, under stationary traffic, if $P^{\text{if}}(n) = B^{\text{if}}(n)$ then, on average, t_n^{if} is increased by 1 and decreased by 1 every d_n^{if} offered PU requests, that is, its mean value is kept constant.

When the traffic is nonstationary, the adaptive scheme will continuously adjust the thresholds in order to meet the objectives if possible, adapting to any mix of traffic. Clearly, in the operation of this simple scheme no assumptions have been made concerning the arrival processes or the distributions of the session duration.

An important consequence of the definition of the interference probabilities $\{P^{\text{if}}(n)\}$ is that now we have the possibility to limit what we call the *interference distribution*. That is, we can define one objective for each of the elements of $\{P^{\text{if}}(n)\}$, $n = 1, \dots, N$, or combinations of them, in order to give less importance (allow higher probabilities) to events that create lower interference (small values of n) and more importance (allow smaller probabilities) to events that create higher interference (high values of n).

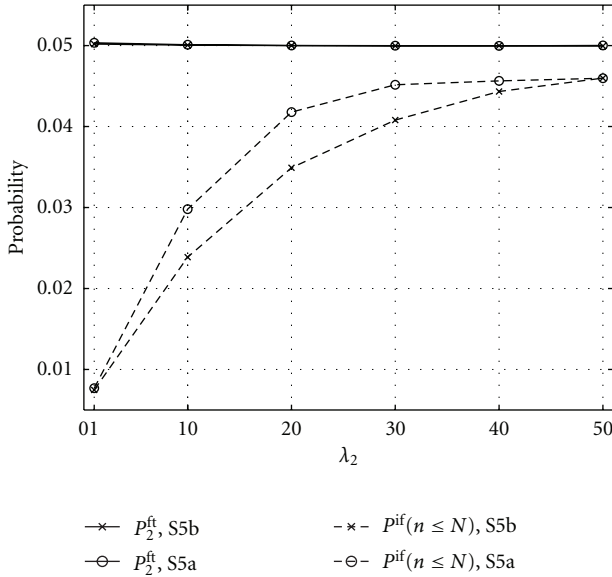
Figure 5 describes the procedure followed at a SU arrival to decide upon the acceptance or rejection of the new request. If the system defines multiple objectives for the interference and therefore manages multiple thresholds, then t^{if} would be the minimum of all these thresholds.

4.1. Numerical Results. The adaptive scheme has been evaluated in systems 5a and 5b by simulation. We used the parameter values defined in Section 3.

As an example, let us consider $P^{\text{if}}(n \leq N) = \sum_{n=1}^N P^{\text{if}}(n)$; that is, the fraction of PU arrivals that are interfered by SUs. Figure 6 shows the variation of P_2^{ft} and the interference with the SUs arrival rate when the objectives are $B_2^{\text{ft}} \leq 0.05$ and $B^{\text{if}}(n \leq N = 8) \leq 0.1$. As observed, the scheme is able to limit P_2^{ft} and $P^{\text{if}}(n \leq N)$ to their objectives or below, and

- (1) D , D^{ft} and D^{if} are internal flags.
- (2) Execute at every SU arrival:
- (3) if $x_1 N + x_2 < C$: (free resources available)
- (4) if $b(x) + b_2 \leq t^{\text{ft}}$ then $D^{\text{ft}} = 1$
else $D^{\text{ft}} = 0$
- (5) if $b(x) + b_2 \leq t^{\text{if}}$ then $D^{\text{if}} = 1$
else $D^{\text{if}} = 0$
- (6) $D = D^{\text{ft}} \& D^{\text{if}}$
- (7) if $D = 1$ then *accept SU request*
else *reject SU request*
- (8) else *reject SU request*

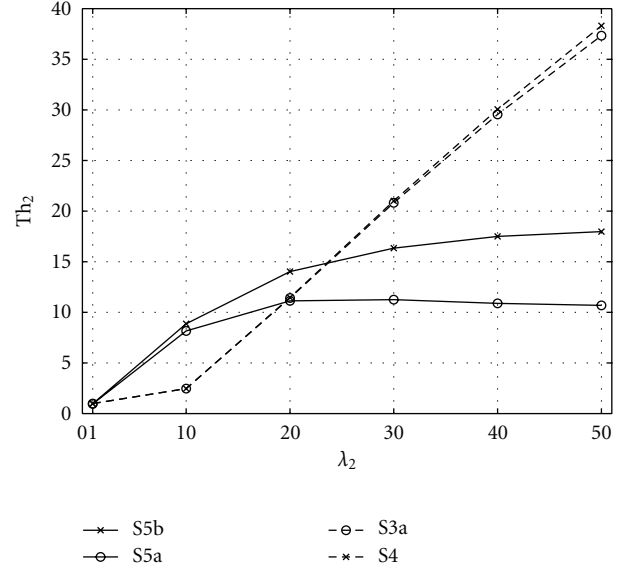
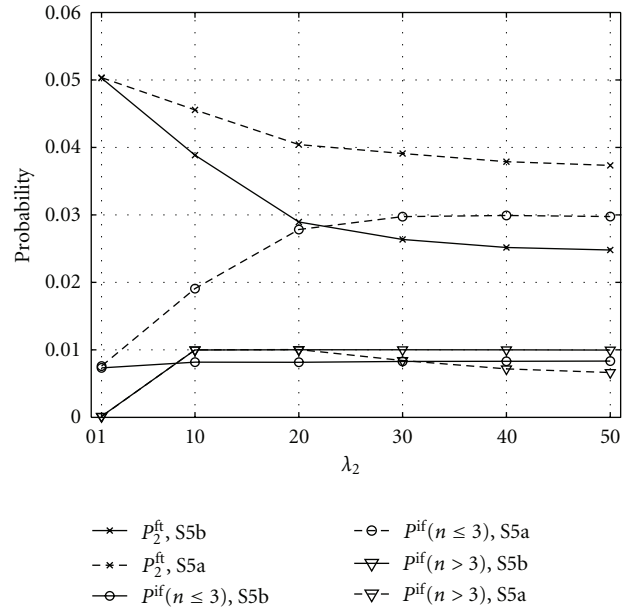
FIGURE 5: Admission control scheme for SUs.

FIGURE 6: P_2^{ft} and interference ($P^{\text{if}}(n \leq N)$) with λ_2 in S5a and S5b.

the interference is lower when repacking is used. Note that the limiting objective in both systems is B_2^{ft} , as $P^{\text{if}}(n \leq N)$ remains below its objective. In other words, t^{ft} is lower than $t^{\text{if}}(n \leq N)$ in both systems for the load range considered. Note also that we have chosen a wide arrival rate range to show the effectiveness of the adaptive scheme. However, if the system does not reserve resources to accommodate SHs then $P_2^{\text{ft}} > 0.05$ even for small values of λ_2 .

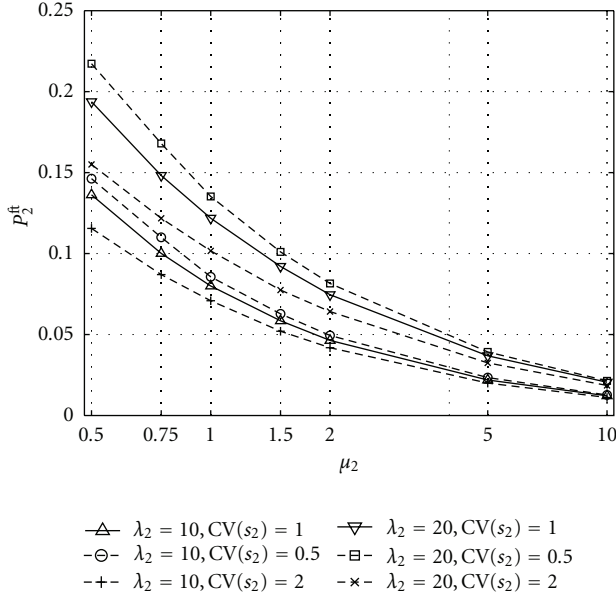
Figure 7 shows the variation of the SUs throughput with the SUs arrival rate. As a reference, we also plot the results obtained for systems 3a and 4. Recall that systems 3a and 5a do not support SH, deploy CAP but no repacking, while systems 4 and 5b do support SH, deploy CAP and repacking. However, S5a and S5b deploy the adaptive AC scheme, while S3a and S4 do not.

We consider that system loads that make $P_2^{\text{ft}} > 0.1$ are of no practical interest. Although not shown, in systems 3a and 4, $P_2^{\text{ft}} > 0.1$ for $\lambda_2 > 20$. Then, restricting to the load range of interest for S3a and S4, Th_2 is higher in S5a and S5b than in S3a and S4. The improvement comes from the fact that limiting P_2^{ft} increases the rate of SUs that complete service successfully. As λ_2 keeps on growing, the blocking of SU setup

FIGURE 7: SUs throughput with λ_2 in S5a, S5b, S3a and S4.FIGURE 8: P_2^{ft} and interference with λ_2 in S5a and S5b.

requests increases as the AC scheme must keep on limiting P_2^{ft} . This higher SUs blocking limits the SUs acceptance rate and therefore the growth of Th_2 .

As another example, let us consider $P^{\text{if}}(n \leq 3)$ and $P^{\text{if}}(n > 3)$; that is, the fraction of PU arrivals that perceive low interference ($n \leq 3$) and the fraction that perceive high interference ($n > 3$). Figure 8 plots P_2^{ft} and the interference as a function of the SUs arrival rate, when the objectives are $B_2^{\text{ft}} \leq 0.05$, $B^{\text{if}}(n \leq 3) = 0.03$ and $B^{\text{if}}(n > 3) = 0.01$. The scheme is able to limit P_2^{ft} , $P^{\text{if}}(n \leq 3)$ and $P^{\text{if}}(n > 3)$ to their objectives or below. For $\lambda_2 \leq 20$ the limiting objective in S5a and S5b is $B^{\text{if}}(n > 3)$, as P_2^{ft} and $P^{\text{if}}(n \leq 3)$ are below their

FIGURE 9: Sensitivity of P_2^{ft} to $E[s_2]$ and $\text{CV}[s_2]$ in system 3a.

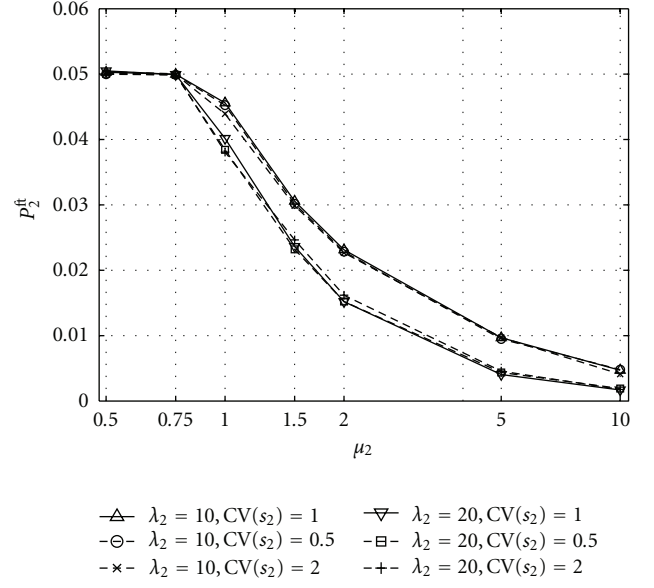
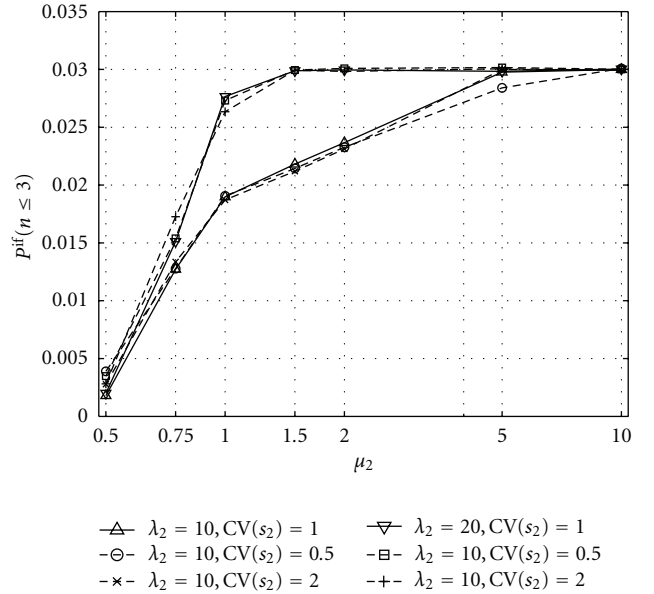
objectives. However, for $\lambda_2 > 20$ the limiting objective in S5a is $B^{\text{if}}(n \leq 3)$, while in S5b is still $B^{\text{if}}(n > 3)$.

4.2. Adaptivity of the AC Scheme. As discussed above, the adaptive scheme can operate with any arrival process and distribution of the session duration. As an example, we study in system 5a the adaptivity of the scheme to different distributions of the SUs session duration random variable (s_2).

We consider three distributions: exponential ($\text{CV}[s_2] = 1$), Erlang ($\text{CV}[s_2] < 1$) and hyperexponential ($\text{CV}[s_2] > 1$). Please refer to any textbook, for example [20], for the definition of the probability density functions of these distributions. For an Erlang- k distribution with $E[s_2] = 1/\mu_2$, the standard deviation and the coefficient of variation are: $\sigma_2 = 1/(\mu_2\sqrt{k})$ and $\text{CV}[s_2] = 1/\sqrt{k}$. We set $k = 4$ to obtain $\text{CV}[s_2] = 1/2$. We use a special type of a two stage hyperexponential distribution that requires only two parameters (mean and standard deviation) for characterization [21]. The standard deviation is selected to obtain $\text{CV}[s_2] = 2$. Note that in our results we also vary the mean ($E[s_2] = 1/\mu_2$), then the offered load (λ_2/μ_2) is maintained constant to make results comparable.

To motivate the interest of deploying adaptive schemes, Figure 9 shows the variation of P_2^{ft} in system 3a. Note that both the CV and the mean of s_2 have a great impact on P_2^{ft} . In fact, in Figure 9 we get one order of magnitude variation in the values of P_2^{ft} for a constant offered load.

The effectiveness of the adaptive scheme to cope with traffic having different characteristics is clearly shown in Figures 10, 11 and 12. The forced termination and interference objectives have been set to $B_2^{\text{ft}} \leq 0.05$, $B^{\text{if}}(n \leq 3) = 0.03$ and $B^{\text{if}}(n > 3) = 0.01$. As in other scenarios, the load of PUs is adjusted such that their blocking probability is 0.01. Observe

FIGURE 10: P_2^{ft} with μ_2 and $\text{CV}[s_2]$ in S5a.FIGURE 11: Interference ($P^{\text{if}}(n \leq 3)$) with μ_2 and $\text{CV}[s_2]$ in S5a.

that the proposed scheme is able to adapt and limit the forced termination and the interference under all conditions.

In Figure 10, we observe that for $\mu_2 < 0.75$ the limiting objective is B_2^{ft} , as the interference probabilities are below their objectives. However, for $\mu_2 > 0.75$ this behavior is reversed. This is due to the fact that to meet one of the interference objectives the rate of admitted SUs into the system is reduced (the threshold is reduced), as observed in Figures 11 and 12. Note that a similar phenomenon was described in Figure 8. Clearly, for $\lambda_2 = 10$ and $\mu_2 \in [1, 5]$ the limiting objective is $B^{\text{if}}(n > 3)$, while for $\mu_2 > 5$ the limiting objective is $B^{\text{if}}(n \leq 3)$. For $\lambda_2 = 20$ and $\mu_2 > 1$ the limiting

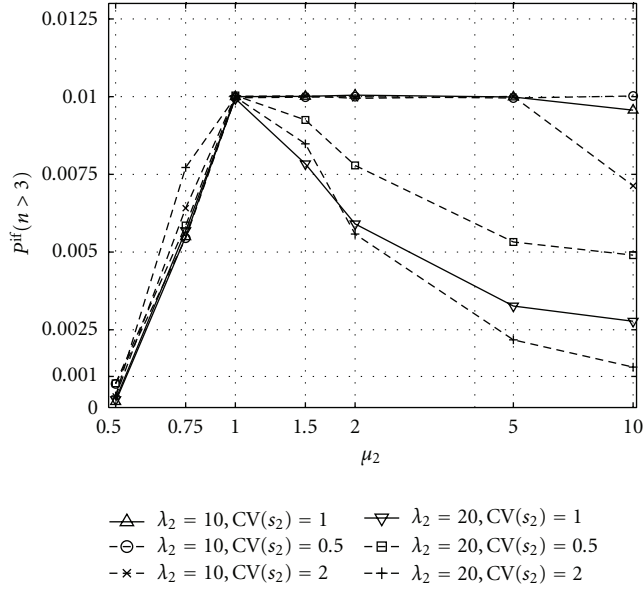


FIGURE 12: Interference ($P^{if}(n > 3)$) with μ_2 and $CV[s_2]$ in S5a.

objective is $B^{if}(n \leq 3)$, that is, the fraction of PU arrivals experiencing low interference ($P^{if}(n \leq 3)$) is at its objective or close, while the fraction experiencing high interference ($P^{if}(n > 3)$) is considerably below its objective.

Finally, if we compare Figures 9 and 10 we conclude that the operation of the adaptive scheme makes P_2^{if} insensitive to the distribution of the SUs service time, which is an additional robustness advantage. A similar conclusion can be obtained for $P^{if}(n \leq 3)$ and partially for $P^{if}(n > 3)$.

5. Conclusions

We studied the effectiveness of the Fractional Guard Channel admission policy to guarantee the QoS perceived by SUs, defined in terms of their forced termination probability. We modeled the system as a CTMC which was validated by computer simulation. Results showed that, contrary to what has been proposed, the throughput of SUs cannot be maximized by configuring the reservation parameter. We also showed that the probability of forced termination can be limited by setting appropriately the reservation threshold.

We also studied the QoS perceived by PUs, defined in terms of the interference caused to PU communications by the operation of SUs. We proposed and evaluated different mechanisms to reduce the interference based on simple spectrum access and channel repacking algorithms. In this case, to cope with the state explosion as the number of system channels grows, we resorted to simulation models that were validated by developing analytical models for systems of manageable size. We compared the interference in a system that uses the proposed mechanisms with the interference in a system that uses the common random access scheme. Numerical results showed that the interference reduction can be of one order of magnitude or higher when using the new mechanisms with respect to the random access case.

Finally, we proposed and evaluated a novel adaptive admission control scheme for SUs that is able to limit simultaneously the probability of forced termination of SUs and the interference. The operation of our scheme is based on simple balance equations which hold for any arrival process and holding time distribution. Our proposal has two relevant features, its ability to guarantee a certain degree of QoS for PUs and SUs under any traffic characteristics, and its implementation simplicity.

Acknowledgments

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